Illinois' Sinkhole Plain: Classic Karst Terrain of the Midwestern United States

Geological Field Trip Guidebook for the 12th Multidisciplinary Conference on Sinkholes and the Engineering & Environmental Impacts of Karst
January 10–14, 2011
St. Louis, Missouri, USA

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Guidebook 39 2011

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Cover photograph: *The incised channel (Figure 34a) showing the relationship between the sinuosity of the channel and the texture of the bedding plane surface. (Photograph by Samuel V. Panno.)*

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ABSTRACT

This field trip is dedicated to the men and women of the Monroe and Randolph County Health Departments, especially Joan Bade, for their valiant efforts in educating lawmakers, the public, and industry on how to live in harmony with karst terrain and for strictly enforcing regulations for the good of the community. The field trip will take its participants into the heart of Illinois' sinkhole plain, which lies along the western flank of the Illinois Basin. Here, the loess- and till-covered Mississippian-age limestone bedrock has given rise to a landscape of more than 10,000 cover-collapse sinkholes, active branchwork caves, and large picturesque springs. Participants will cross lands with sinkhole densities greater than 80 sinkholes/km^2 and visit a karst window, several large karst springs, and a saline spring. The stop at Falling Springs includes a 15-m-high waterfall discharging from a small cave along a tufa-encrusted bluff. The saline spring (one of at least 40 known in the Illinois Basin) has created a black, sulfide-coated elliptical depression due to mixing corrosion and/or the microbial generation of sulfuric acid. The spring discharges to a small stream where mats of white, filamentous, sulfide-oxidizing bacteria abound. The field trip participants will learn about the karst geology and hydrogeology of Illinois' sinkhole plain and the past and ongoing research involving the use of chemistry, isotopes, and an rRNA gene in the identification and sources of nitrate and bacteria in contaminated wells and springs, the use of stalagmites in nearby caves to study the periodicity of large earthquakes (some of which were generated by the nearby New Madrid Seismic Zone), the significance of saline springs in the Illinois Basin, and mapping efforts to identify and catalogue karst features in the state of Illinois.

INTRODUCTION

The Illinois sinkhole plain is located in St. Clair, Monroe, and Randolph Counties in the highlands of southwestern Illinois. This area exhibits classic karst geology and hydrogeology and contains a high density of cover-collapse sinkholes (Figure 1). Steep bluffs up to 60 m high separate the highlands of the sinkhole plain from the lowlands of the Mississippi River valley to the west. The climate is temperate, and mean annual precipitation is 102 cm (Wendland et al. 1992). Bedrock in the sinkhole plain is Mississippian-age limestone overlain by a relatively thin layer (0 to 20 m thick) of Pleistocene-age glacial till and loess. The area is replete with cover-collapse sinkholes, large flashy springs, and large branchwork cave systems. Outcrops and road cuts in the area reveal limestone bedrock festooned with solution-enlarged crevices and overlain by a well-defined epikarst (Panno et al. 1996).

The sinkhole plain is predominantly rural, and the dominant land use is row crop agriculture. An improvement in the highway system within and north of Waterloo, Illinois, in the 1990s, however, reduced commuting times to St. Louis, Missouri, which resulted in a large influx of people who were unprepared for the problems inherent in karst terrain: land subsidence and poor groundwater quality. However, because of karst education programs initiated by Joan Bade in the early 1990s and continued by John Wagner (Monroe and Randolph County Health Departments), the area's residents are learning to live with the vagaries of karst terrain. In addition, the introduction of a public water system in the area has alleviated water quality problems for many of the residents.

History of the Sinkhole Plain

Native Americans, including the mound builders of the Cahokia area, inhabited southwestern Illinois for thousands of years prior to the arrival of French explorers in the late seventeenth century. Eventually English, Irish, Scottish, and Welsh settled in the area and, after many bloody conflicts, displaced the Native Americans. One of the first towns to be built was Bellefontaine (now Waterloo), which was initially a trading post and a waypoint for western expeditions (including Lewis and Clark's 1803 expedition). In the early part of the

Figure 1 Aerial view of the Illinois sinkhole plain looking west across the Mississippi River valley toward Missouri. (Photograph by Joel M. Dexter.)

nineteenth century, German immigrants who settled in the area worked for landowners and were paid in land. Because of this practice, most of the land was eventually owned by Germans, and much of this area is still farmed today by their descendants (Klein 1967). At present, nearly 70% of land use in the sinkhole plain is used for row crop agriculture (U.S. Department of Agriculture 1987).

Geology and Hydrogeology

The sinkhole plain of Illinois lies on the western flank of the Illinois Basin where Mississippian-age carbonate rocks are at and near the surface. The thin blanket of sediments that overlie the bedrock consist of glacial till overlain by loess that typically is less than 15 m thick (Herzog et al. 1994). Bedrock is Salem, St. Louis, and Ste. Genevieve Limestones that dip about 3 degrees to the east toward the center of the Illinois Basin (Figures 2 and 3). Karstification occurs primarily in the St. Louis and Ste. Genevieve Limestones, which are 97% calcite; consequently, these formations are highly soluble. Numerous fractures in the bedrock, roughly trending north to south and east to west have developed into solution-enlarged crevices that, along with numerous branchwork-type cave systems, make up the shallow karst aquifer. These limestones outcrop along road cuts, quarries, and bluffs along the Mississippi River and subcrop beneath Pleistocene-age glacial till and loess deposits that range from 0 to 15 m thick within parts of St. Clair, Monroe, Randolph, and Jackson Counties. The carbonate rocks dive beneath Pennsylvanian-age shale to the east; on the west, the sinkhole plain is bounded by 60- to 100-m bluffs of the Mississippi River and its floodplain. Structures in the area include the northwest-southeast–trending Waterloo-Dupo Anticline and Columbia Syncline to the north and Valmeyer Anticline to the south (Nelson 1999).

Research in the Sinkhole Plain

The Illinois State Geological Survey and the Illinois State Water Survey have been conducting cave and karst research in Illinois' sinkhole plain since the early 1990s. The classic karst terrain in southwestern Illinois provides an excellent laboratory for research on karst features, mapping techniques, paleoclimate and cave formation, earthquake periodicity of the New Madrid Seismic Zone, groundwater contamination, background ion concentrations in shallow groundwater, and CO_2 sequestration. Past and ongoing research activities in this area are described next.

Karst Mapping. During 2010, Luman and Panno (2011) began examining historic and recent aerial photography acquired over the sinkhole plain. Using GIS (Geographic Information Systems) technology, they were able to digitize every sinkhole visible on aerial photographs and compare their locations to the closed depressions on current U.S. Geological Survey (USGS) 7.5-minute topographic maps. In addition, they documented lineaments visible on shaded relief images produced from large-scale USGS Digital Elevation Models (DEMs). All of these data were compared with bedrock geology maps of the area and with field data on orientations of solution-enlarged crevices, caves, and spring locations.

Cover-collapse sinkholes in Monroe County tend to form in the loess and glacial till that overlie the creviced Mississippian-age St. Louis and Ste. Genevieve Limestone formations (Figures 1 and 4). Sinkholes are concentrated in two major areas of the county, which are largely encompassed by the USGS Waterloo and Renault topographic quadrangles. In these areas, sinkhole densities are as high as 95/km^2 (Angel et al. 2004; Panno et al. 2008a, 2008b, 2008c) and contain relatively long (>10 km) to medium-length (1 to 2 km) caves and abundant solution-enlarged crevices. Work by Panno et al. (2011) has shown that within the sinkhole plain, sinkhole size is proportional to the size of underlying crevices and conduit systems. The size and morphology of the cover-collapse sinkholes in this region are directly related to water table depth and storage capacity of the underlying crevices and conduits.

Sinkhole density within the Waterloo Quadrangle is greatest on upland areas adjacent to Fountain Creek, the prominent stream valley in the quadrangle. The largest sinkholes are situated towards the headwaters of known and suspected cave systems discharging into Fountain Creek. Shallower, smaller sinkholes are found along the eastern flanks and near the nose of the Waterloo-Dupo Anticline.

In the Renault Quadrangle, the underlying bedrock is dominated by the St. Louis Limestone with small occurrences of Salem Limestone along the crest of the Valmeyer Anticline where no sinkholes are found in the overlying sediments. Dense clusters of sinkholes are found in the Fogelpole Cave groundwater basin, and, particularly along its margin, sinkholes are large and complex. The center of this basin is so karstified that a topographic low of approximately 2.5 km^2 has been created from the resulting coalescence of the sinkhole features (Figure 5).

Preliminary results by Luman and Panno (2011) have shown that the closed depressions on current USGS 7.5-minute topographic maps miss about 30% of the sinkholes that are visible on aerial photographs, mainly

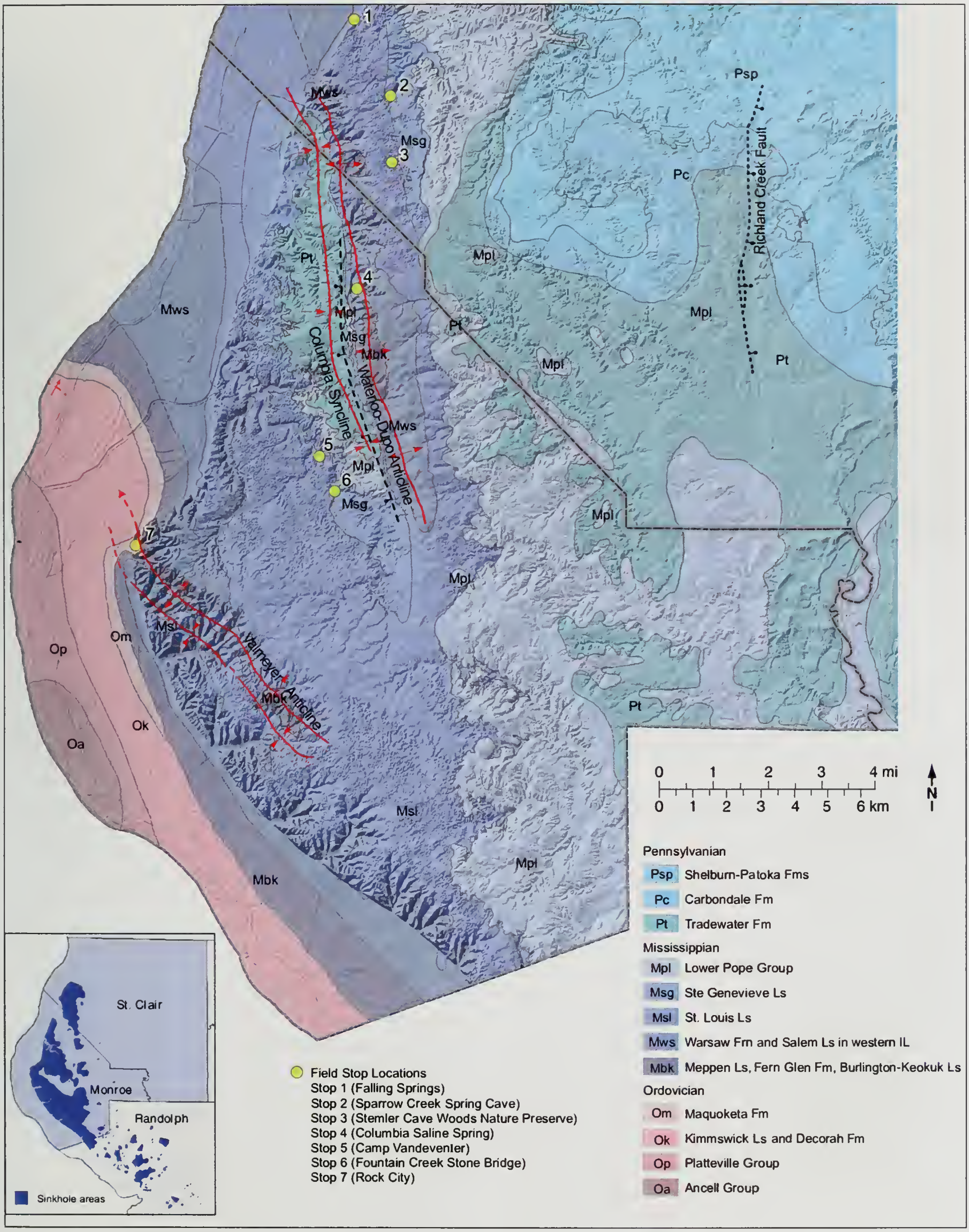

Figure 2 The Illinois sinkhole plain showing the distribution of karst terrain, the structural features present, and major rock units (modified from Luman and Panno 2011). Abbreviations: Fm, Formation; Ls, Limestone.

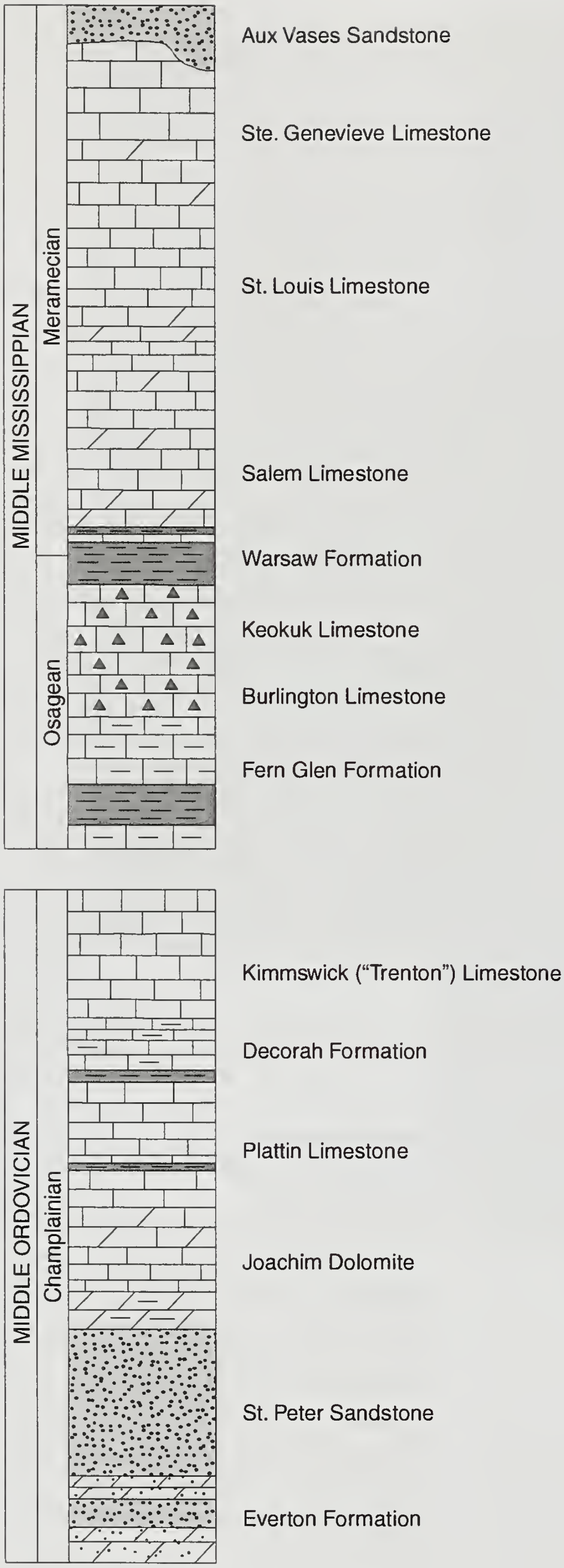

Figure 3 Generalized stratigraphic column of the Middle Ordovician and Middle Mississippian strata in the field trip area (Weibel and Panno 1997).

because many sinkholes are shallower than the typical 10-foot contour interval used on large-scale USGS topographic maps. Luman and Panno (2011) identified over 13,000 sinkholes from aerial photography, which is about 3,000 more than previous mapping by Panno et al. (1996). Preliminary results of work on lineaments in the sinkhole plain revealed two dominant lineament directions: roughly north-south and east-west; these correspond to the orientation of solution-enlarged crevices of the area (Panno, unpublished data).

Cave Research. The sinkhole plain is home to the three longest known caves in Illinois: Fogelpole Cave, Illinois Caverns, and Stemler Cave (Figure 6). Speleothems in the first two caves and Pautler Cave, a shorter cave just west of Waterloo, Illinois, have been found to contain information on paleoclimatic conditions and earthquake activity within the Midwest.

Panno et al. (2004b) found that the timing of deposition of diamicton and silty, fine-grained sediments within secondary passages of Illinois Caverns and Fogelpole Cave could be determined using carbon-14 dating techniques. The sediments were remnants of flood deposits that had been preserved. The $\delta^{13}C$ of the organic carbon within the sediments yielded information as to the types of vegetation present on the land surface between 42,500 years before present (BP) and the present. Results of this work showed that the rate of sediment accumulation in the cave was positively correlated with a higher proportion of drought-tolerant C_4-type vegetation. That is, when climate was drier, vegetation was less and erosion was greater during rain events. Based on these data and mineralogy data indicating most of the cave sediments were from relatively deep soil horizons on the surface, Panno et al. (2004b) suggested that these rainfall events during dry periods probably initiated sinkhole formation and enlargement in the area. Subsequent work, using incision rates within the main passages of the caves adjacent to filled secondary passages, suggested that the caves of southwestern Illinois were initiated by meltwaters of the Illinois Episode of glaciation (Panno et al. 2004a). Paleoclimate research involving stalagmites from these caves and caves in southern Indiana is ongoing and is yielding additional information on the relationship between Pleistocene glaciation and speleogenesis (Chirienco et al. 2010).

An investigation into the origin of small white speleothems in caves of the Illinois sinkhole plain and southeastern Missouri (Figure 7) revealed that speleothem growth was initiated by major seismic events related to the New Madrid Seismic Zone (NMSZ) (Panno et al. 2009). Crevices and/or fractures leading to the caves from the epikarst were apparently enlarged by the earth-

Figure 4 The excavation of a 100-m diameter sinkhole revealed a narrow crevice in the exposed St. Louis Limestone bedrock that leads to a somewhat wider crevice. The wider crevice led down, about 5 m, into a small cave about 0.3 m high and 0.6 m wide through which runoff from rainwater and snowmelt flows (Panno et al. 2009).

quakes, allowing soil water and perched groundwater to seep into the underlying caves. The initiation of white stalagmites was temporally related to the 1811–1812 NMSZ earthquake series. The ages of stalagmites on which the white stalagmites were growing corresponded to prehistoric NMSZ earthquakes known from the dating of nearby liquefaction features (e.g., Tuttle et al. 1999). A subsequent investigation revealed the existence of the white stalagmites and associated older, earthquake-related stalagmites in other midwestern states in the vicinity of the NMSZ (Panno et al. unpublished data). Age-dating has the potential to document additional paleoseismic events in the Midwest and in other seismically active areas of the world.

The caves of the sinkhole plain are the sole habitat of the Illinois cave amphipod (*Gammarus acherondytes*), a federally endangered species. The amphipod was reported to be present in both Illinois Caverns and Stemler Cave as well as a few other caves in the sinkhole plain in the 1970s (Peck and Lewis 1978). Subsequent studies failed to locate the amphipod in Stemler Cave after 1995 (Webb 1995). Using those data, Panno et al. (2006) compared the aqueous environment of Illinois Caverns with that of Stemler Cave to determine environmental differences within the caves. They found that the water flowing through Stemler Cave during low flow conditions was low in dissolved oxygen due to discharge from private septic systems within the groundwater basin. No such conditions were present within the Illinois Caverns streams. The authors speculate that the near-hypoxic conditions within the Stemler Cave groundwater basin may have given the competitive advantage to other invertebrates within the groundwater basin. For an in-depth study of macroinvertebrate biodiversity in caves and springs in the sinkhole plain, see Webb et al. (1998a).

Field trips to the Illinois sinkhole plain would ordinarily include a trip to Illinois Caverns (Frankie et al. 1997, Panno et al. 1999, 2004a), which is the second largest cave in the state and is typical of the area's caves (Figures 8 and 9). Illinois Caverns is a branchwork-type cave that formed along bedding planes within the St. Louis Limestone. Unfortunately, the occurrence of White Nose Syndrome in bats of caves, now extending from eastern Canada and New York to Missouri, has resulted in the closure of Illinois Caverns and many other caves throughout the midwestern United States (Frick et al. 2010). White Nose Syndrome in bats first appeared in the Northeast in 2006. The condition causes white patches on the muzzle and arms of bats and has been attributed to a psychrophilic (cold-tolerant) fungus named *Geomyces destructans*. The fungus disturbs

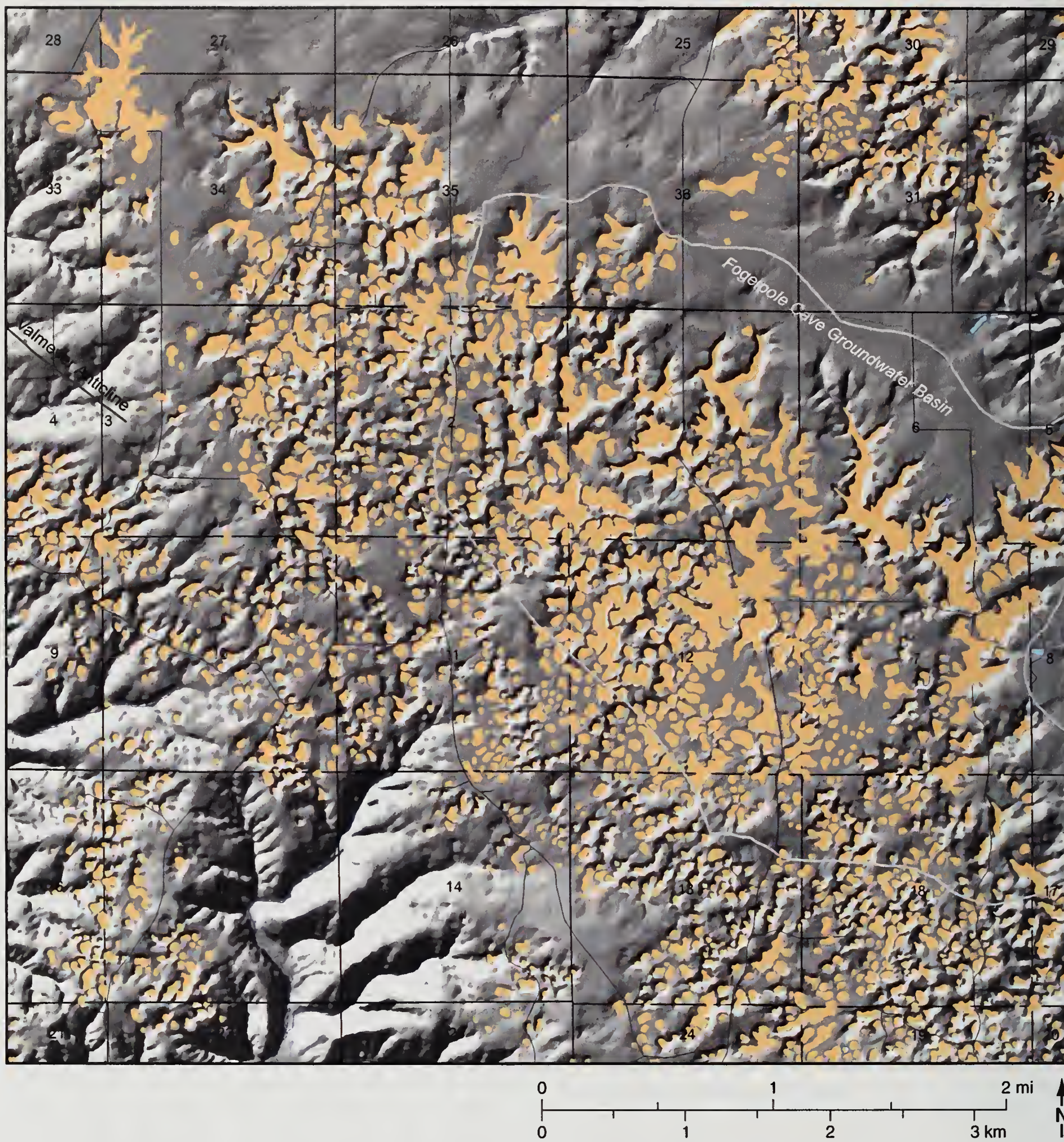

Figure 5 Sinkholes coalesce within the Fogelpole Cave groundwater basin to the point where sinkhole density reaches saturation, resulting in an overall lowering of the elevation of the topography (modified from Luman and Panno 2011).

hibernating bats, resulting in loss of critical fat reserves necessary for survival during hibernation (Frick et al. 2010). The extinction of several bat species is predicted. The source of the fungus is as yet unknown, but it may be spread by both bats and humans. Consequently, caves across the East and Midwest have been closed to humans to protect the remaining bat colonies and/or slow the spread of the fungus.

Groundwater Chemistry and Inorganic Contaminants. The chemical composition of groundwater in the sinkhole plain is primarily a calcium-bicarbonate-type water. During water quality investigations of the springs and wells between 1994 and 2000, the pH of samples from the springs ranged from 6.5 to 8.5; samples from the wells ranged from 6.1 to 7.2 (Panno et al. 1996, Hackley et al. 2007). Dissolved organic

Figure 6 One of three large caves in Monroe County, Illinois Caverns is a branchwork-type cave with an active stream channel that drains the Illinois Caverns groundwater basin. (Photograph by Joel M. Dexter.)

Figure 7 Small white stalagmites in Illinois Caverns tend to grow in clusters either by themselves or on top of older stalagmites. Most of these stalagmites were initiated during the New Madrid Seismic Zone earthquake series of 1811–1812 (Panno et al. 2009).

carbon from the springs ranged from 1.7 mg/L to nearly 14 mg/L, which is more typical of surface water than groundwater (typically <2 mg/L for groundwater). Parameters such as temperature, fluoride, chloride, and carbon isotopes ($\delta^{13}C$) fluctuated seasonally for most of the springs sampled, indicating a relatively rapid connection between the karst aquifer and the influx from surface water. Tritium concentrations in spring water from the study area were between about 4 and 8 tritium units, which were similar to local precipitation values, also indicating recent recharge from surficial sources (Hackley et al. 2007). Considering the relatively rapid influx of recharge water from the surface environment to the shallow karst aquifer, it is not surprising that much of the groundwater in the sinkhole plain has been contaminated by anthropogenic sources. Both spring

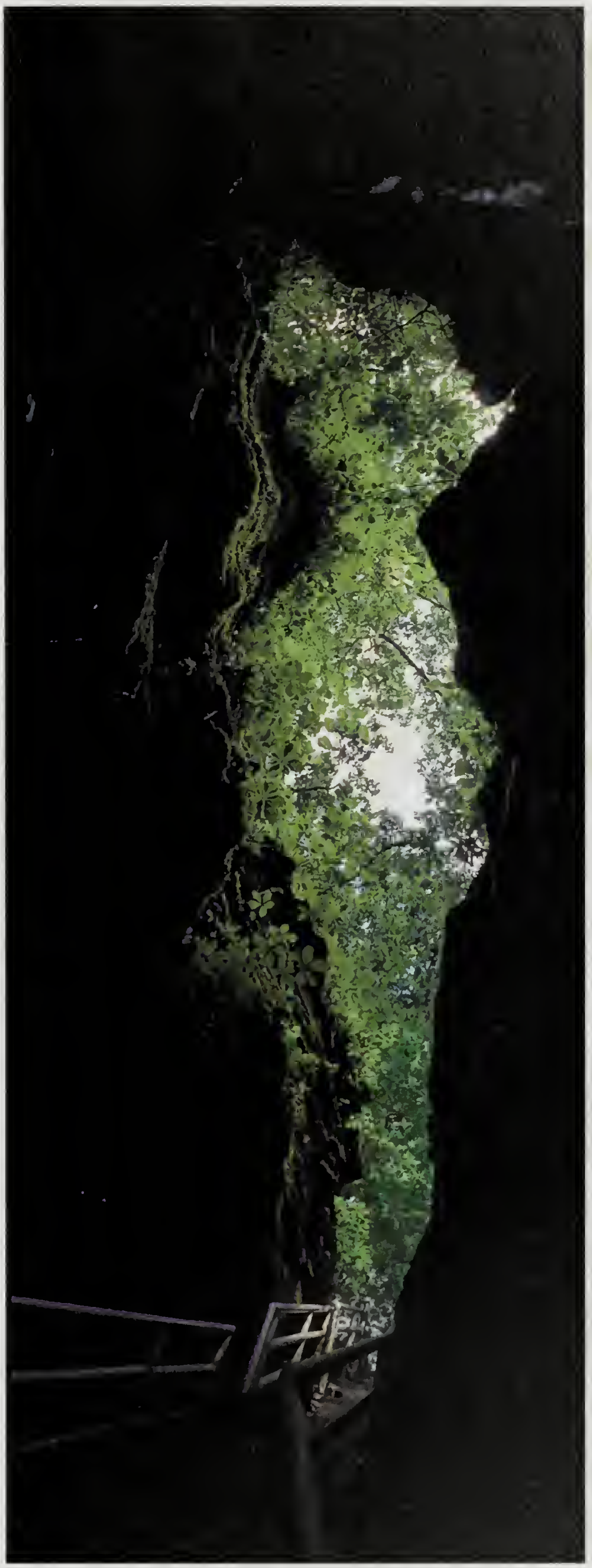

Figure 8 The entrance to Illinois Caverns, as viewed from the cave floor, is an east-west–trending solution-enlarged crevice at the bottom of a sinkhole (Panno et al. 2004a).

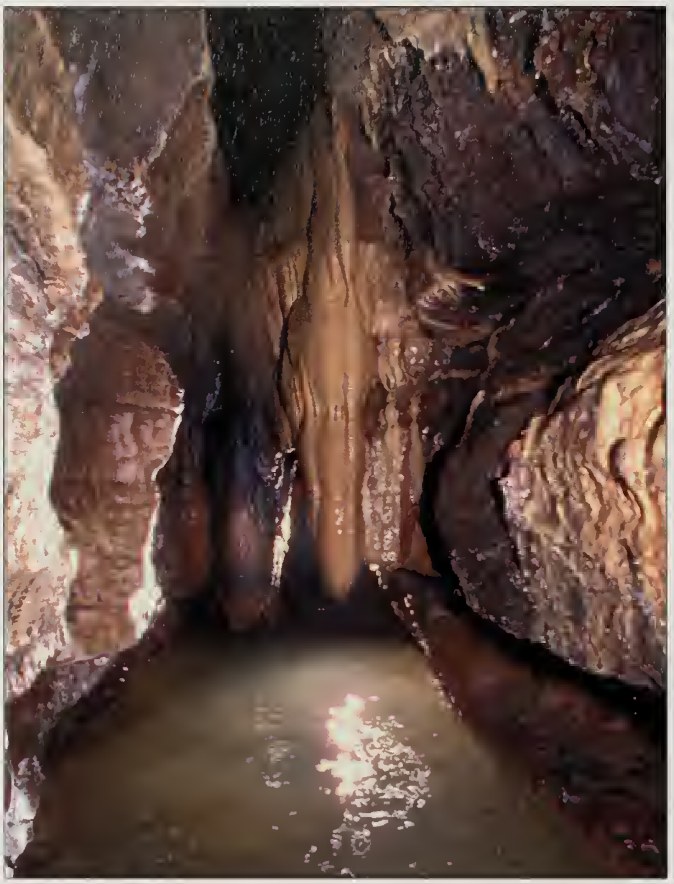

Figure 9 Entrance to the Canyon Passage at Illinois Caverns revealing the active stream passage that flows through the cave (Panno et al. 2004a).

and well water in the sinkhole plain contain elevated concentrations of nitrate nitrogen (NO_3-N), pesticides, and bacteria (Panno et al. 1996, Webb et al. 1998a, Hackley et al. 2007, Kelly et al. 2009).

In the 1990s, nearly half the residents of the sinkhole plain area in southwestern Illinois got their drinking water from uncased bedrock wells in the karst aquifer at depths of 20 to 100 m. Water quality investigations estimated that about 18% of the wells in this region had NO_3-N concentrations greater than the U.S. Environmental Protection Agency drinking water standard of 10 mg/L. All of the springs sampled and 50% of the wells had NO_3-N concentrations greater than background levels of ~2.2 mg/L (Panno et al. 2006), suggesting considerable input of NO_3-N from sources other than natural soil organic matter (Hackley et al. 2007). The sinkhole plain region is dominated by row crop agriculture, but during the last two decades the area has undergone a high degree of urban development. Between 1997 and 2003, more than 20,000 ha were urbanized in the seven counties incorporating the sinkhole plain and karst aquifer region of southwestern Illinois (Southwestern Illinois Resource Conservation and Development, Inc. 2005). Thus, the major sources of nitrate other than naturally occurring soil organic matter include agricultural fertilizers, livestock facilities, and sewage and septic discharge. Ten springs were sampled for six consecutive seasons and 17 wells for two seasons to examine the variation in geochemical parameters and determine the major source of elevated NO_3-N in the groundwater of the sinkhole plain (Hackley et al. 2007). Nitrate-N concentrations in the springs ranged from 1.7 to 7.5 mg/L. The wells showed much greater variations, ranging from below detection limits to 81 mg/L. Figure 10 shows NO_3-N concentration versus depth for the wells. The shallowest wells contained the greatest NO_3-N concentrations, but even very deep wells contained concentrations well above background levels. Those samples containing elevated NO_3-N typically contained elevated chloride also, suggesting septic or livestock contamination (Figure 11).

Nitrogen and oxygen isotopes of the nitrate were measured for samples collected from both springs and wells. The results for spring samples indicated the nitrate source was dominated by fertilizer and/or soil organic matter nitrogen and that some denitrification had occurred in the karst environment (Hackley et al. 2007). Many of the nitrate isotopic results for the wells were similar to the results for the bulk of the samples from springs; however, several of the well samples had $\delta^{15}N$ and $\delta^{18}O$ values that were shifted toward values more representative of septic and livestock sources (Figure 12). For those wells with the greatest NO_3-N concentrations (>13 mg/L), the data indicated that the source was primarily from septic and livestock waste. Nitrate in wells with NO_3-N concentrations between about 2 and 12 mg/L was primarily from fertilizer and soil organic matter. The isotopic results of a few of the well samples also showed significant denitrification (Hackley et al. 2007).

Bacterial Contamination. Within and near the sinkhole plain, 16 springs, 64 domestic wells, and the Illinois Caverns cave stream were sampled for bacteria at multiple times between 1994 and 2000 (Kelly et al. 2009). Bacterial colonies in spring water samples included bacteria commonly found in soils and surficial aqueous environments, and enteric bacteria. All spring and stream samples had detectable concentrations of total coliforms (TC) and total aerobic bacteria (TA). More than 92% of the spring water samples and streams in Illinois Caverns had detectable concentrations of both fecal coliforms (FC) and fecal enterococci (FE) (Kelly et al. 2009). Counts for TA were commonly >3 million colony-forming units (cfu/100 ml); TC typically ranged from a few 100 to >4,800 cfu/100 ml; FE were from 0 to >4,800 cfu/100 ml; and FC were from 0 to >2,400 cfu/100 ml (Hackley et al. 2007). Illinois

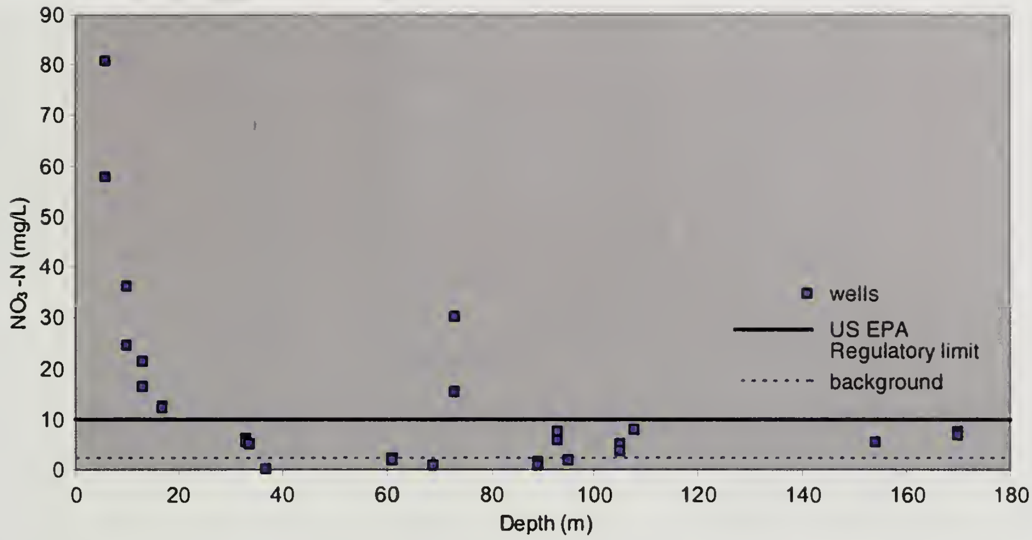

Figure 10 Nitrate (NO_3-N) concentrations versus depth for wells sampled in southwestern Illinois (modified from Hackley et al. 2007).

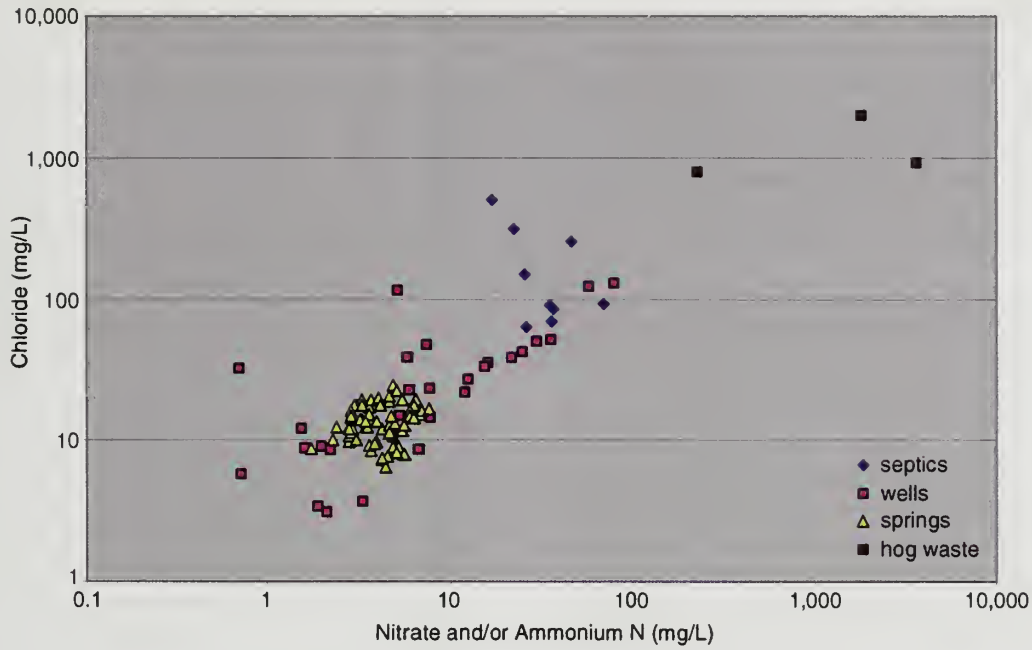

Figure 11 Chloride versus nitrate and ammonium concentrations (total inorganic nitrogen measured) of wells, springs, septic systems, and livestock facilities (modified from Hackley et al. 2007).

water quality regulations require that water suitable for primary contact must not have an average concentration of FC >200 cfu/100 mL for five samples collected over a period of 30 days. Furthermore, 10% of the samples may not have concentrations exceeding 400 cfu/100 mL (Illinois Environmental Protection Agency-Illinois Pollution Control Board 1999). Figure 13a shows FC concentrations found in 10 springs. Bacterial contamination occurred in the springs and cave streams throughout the year (Figure 13a), suggesting that wastewater discharge, which is not seasonally variable, is a greater problem than livestock waste. Hog manure is applied to fields only in the fall and spring, and, during the winter, cattle manure is less subject to decomposition and mobilization and thus less likely to enter the aquifer/cave systems (Kelly et al. 2009).

The types of bacteria in well-water samples were similar to those found in the springs, but at lower concentrations. Tests for TA detected them at least once in 58 of the 64 wells, suggesting that groundwater in the capture zones of these wells was generally oxygenated.

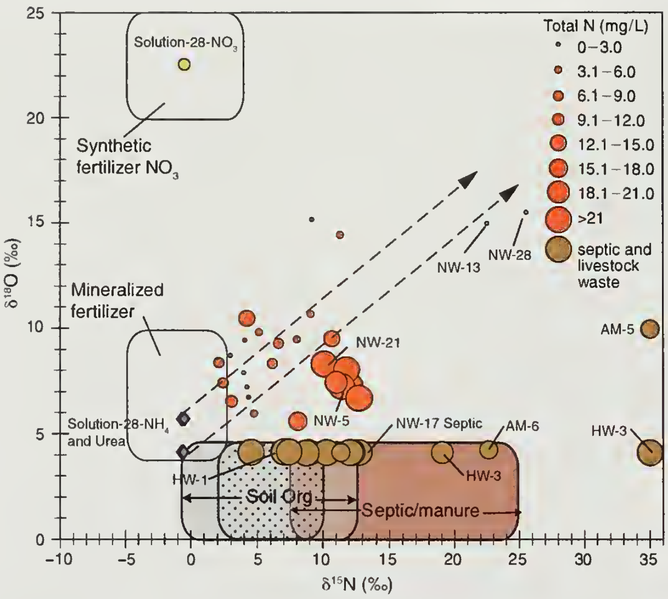

Figure 12 Isotopic composition of nitrate (orange) and possible sources of nitrate in well-water samples including fertilizer, septic systems, and livestock waste. Predominant domains of nitrate sources and typical trend for denitrification (arrows) are included. The $\delta^{18}O$ of nitrate that would be expected from reduced forms of nitrogen was calculated to depict the composition expected for nitrification processes. The calculated values are in excellent agreement with the measured $\delta^{18}O$ NO_3 for the septic system sample NW-17 (from Hackley et al. 2007).

The TC were detected at least once in 63% of the wells, but at concentrations typically much lower than in the spring and cave samples. FC or FE were detected at least once in 23 wells, generally at low concentrations. About half of the detections were <10 cfu/100 mL, and the maximum concentration was 198 cfu/100 mL. The state and county drinking water regulations require <80 cfu/100 mL for TC and no FC in residential well water. All bacterial indicators were less likely to be detected, and concentrations were lower, in wells in non-karst than in karst and covered karst areas. Wells located in areas with livestock had the highest concentrations of FE, and the water chemistry was indicative of fecal contamination (elevated NO_3-N and Cl^-). Shallow wells were more likely to have detectable TC, FC, and FE and at higher concentrations regardless of terrain; wells <20 m deep (all in covered karst) were the most vulnerable (Figure 13). The inverse relationship between well depth and FE indicates that deeper groundwater is somewhat protected from surface contamination. However, TC, FC, and/or FE were found in 10 of the 18 wells in karst or covered karst that were >100 m deep, indicating shallow groundwater was entering the well bore (Kelly et al. 2009).

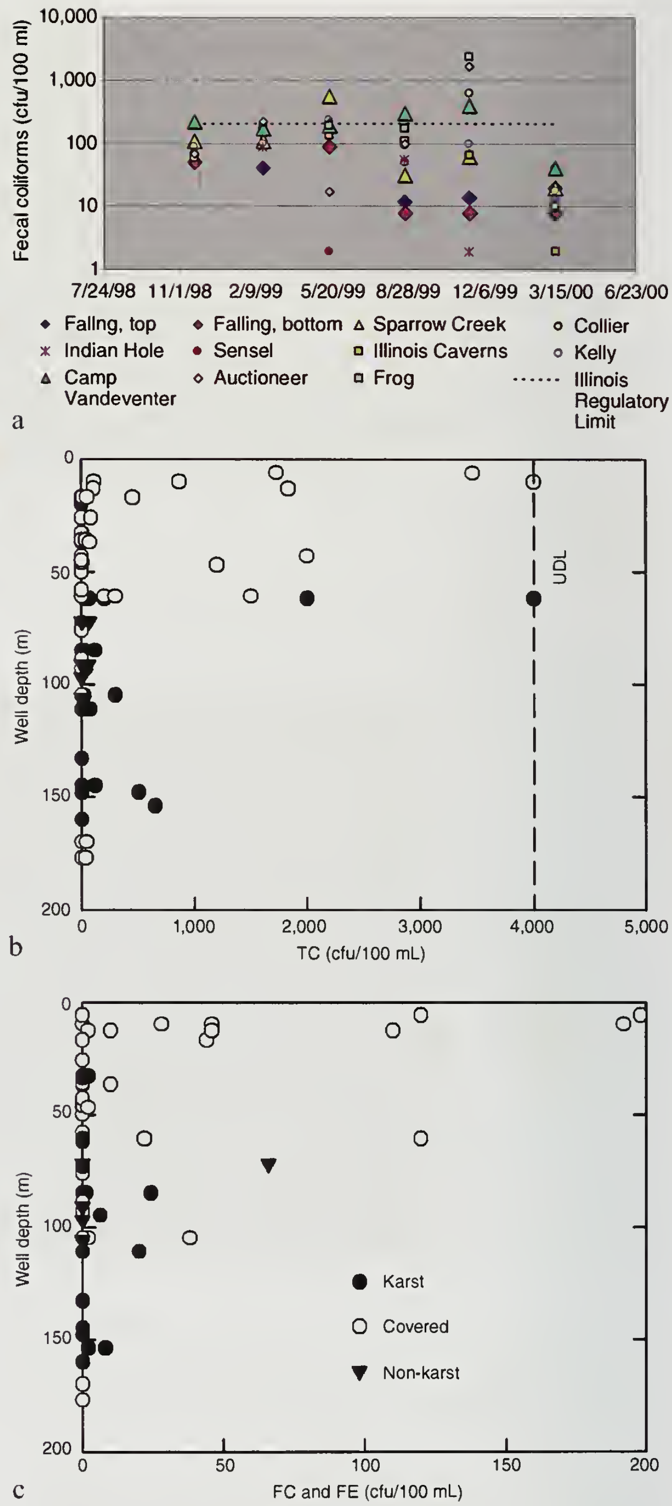

Figure 13 (a) Distribution of fecal coliform concentrations in water samples from springs in southwestern Illinois. Enlarged symbols are springs visited on the field trip (modified from Kelly et al. 2009). (b) Total coliforms versus well depth. (c) Fecal coliforms and fecal enterococci versus well depth. Symbols touching the dotted line represent samples with total coliform concentrations greater than the upper detection limit (UDL) of 4,000 cfu/100 mL (modified from Kelly et al. 2009).

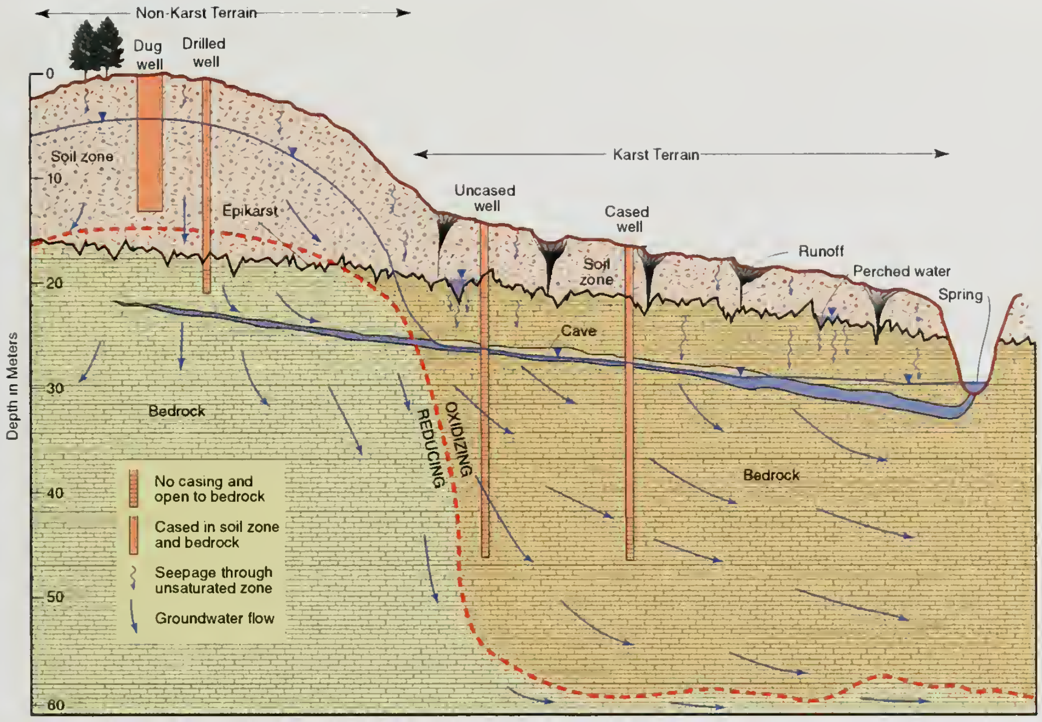

Figure 14 A conceptual model of the hydrogeology and redox conditions of the karst aquifer in the sinkhole plain for a groundwater basin (from Kelly et al. 2009).

A negative association was observed between TC and well casing length in the karst region, suggesting that well construction practices in areas with significant dissolution features can contribute to bacterial contamination of the aquifer. Drilled wells are often cased and grouted only through the unlithified sediments and into the top of bedrock; 16 of 40 wells for which data were available were cased into the bedrock 3 m or less. This construction practice allows wells to be exposed to shallow groundwater that often migrates through conduits in the bedrock, possibly resulting in the mixing of contaminated shallow groundwater with uncontaminated or less contaminated groundwater from deeper bedrock (Panno et al. 1996).

When comparing water quality among springs, caves, and wells in the study area, it is important to consider the differences in hydrogeological and geochemical conditions. Springs are outlets for all shallow groundwater in a particular karst groundwater basin and represent a mixture of water throughout the basin, often from areas with different land uses. Thus, although contamination from any point in the groundwater basin may be detected in the spring discharge, it will be diluted by water coming from uncontaminated areas. Groundwater collected from wells generally represents a smaller source area and will have longer residence times. Contaminated wells were less likely than springs to show signs of dilution. Thus, wells in the study area generally had lower NO_3-N concentrations than springs did (median 0.66 mg/L vs. 3.8 mg/L), but a wider range of values. Sixteen percent of well samples had NO_3-N greater than 10 mg/L; none of the spring or cave samples exceeded 10 mg/L.

Kelly et al. (2009) developed a conceptual model of the region (Figure 14). In covered karst areas and typically along the margins groundwater basins, the water table is shallow, and wells finished above the bedrock are vulnerable to surface contamination. For wells <20 m deep, median NO_3-N and Cl^- concentrations were 12.2 and 24 mg/L, respectively; in deeper wells, median NO_3-N and Cl^- concentrations were 0.19 and 12 mg/L. Pesticides and FC were detected in 60% and 31% of the shallow well samples, respectively, and 20% and 7% of the deeper well samples. In karst areas, the water table is within the bedrock, and there were no wells shallower than 20 m. Groundwater in the karst areas is generally well oxygenated. At least four of the wells sampled in the karst setting intersected a large crevice or cave. In covered karst areas, the groundwater is generally less oxygenated and often anoxic (Figure 14). Conditions are generally fully anoxic in the bedrock in the covered karst region. The median redox potential value in covered karst wells deeper than 20 m was 100 mV lower than in karst areas.

To help distinguish the source of bacterial contamination of groundwater in the sinkhole plain, we recently initiated a study to identify fecal sources using the Bacteroides-Prevotella 16S rRNA gene as part of a new molecular method termed hierarchical oligonucleotide

primer extension (HOPE) (Hong et al. 2009). The HOPE method has been successfully demonstrated to identify and distinguish sources of fecal contamination among human, cow, pig, and dog feces in a rapid and throughput manner. As part of that investigation, 10 springs were sampled in 2009, including Falling Springs, Sparrow Creek, and Camp Vandeventer, which are being visited on this field trip. Of the eight springs that were contaminated with fecal bacteria, one was identified as being predominantly from humans (Sparrow Creek), two predominantly from pigs (including Falling Springs), two predominantly from pigs with possibly some human sources (including Camp Vandeventer), and three from a combination of humans, pigs, and cows. These results generally compared well with our predictions based on known land uses, but, for two of the sites, the source tracking method gave unexpected results. This study was recently expanded to look at karst water resources in Wisconsin, Kentucky, and Missouri.

Efforts by the Monroe and Randolph County Health Departments

In the early 1990s, Joan Bade of the Monroe and Randolph County Health Department recognized the problems associated with the karst terrain and well-water quality in the Illinois sinkhole plain. These problems were exacerbated in the mid-1990s when Route 3 through Waterloo, Illinois, was expanded to a four-lane highway, which significantly cut the commute time to and from St. Louis, Missouri, and resulted in many new residents moving to the area. As head sanitarian, Joan Bade garnered help from the Illinois State Geological Survey, the Illinois Environmental Protection Agency, the Illinois State Health Department, and local schools and led a very successful campaign to educate the people of Monroe and Randolph Counties about the problems of karst terrain. With the support of these organizations, she organized and led annual field trips and conferences to spread the word about the problems to regulators and lawmakers. She strictly enforced existing regulations regarding the siting of septic systems and requests for housing construction in the face of considerable opposition. She was instrumental in changing weak regulations regarding the siting of septic systems and permitting for housing and well construction. In addition, Bade successfully acquired grants from the Illinois Environmental Protection Agency and hired a karst educator to educate the citizens of the area. John Wagner, Bade's assistant beginning in 1995, later became head sanitarian after Bade took a job at the Illinois Department of Natural Resources. The health department is now split into a department for each county. Wagner is head of both Monroe and Randolph County's health departments and continues, with the help of Adrian Coring, to educate the citizens of the sinkhole plain and to enforce regulations. Today, the term "karst terrain" is well-known in the area, and the citizens understand its meaning and its implications for water quality, land stability, and flooding.

During the late 1990s and early 2000s, a municipal water system was made available to many of the residences of the sinkhole plain, alleviating persistent water quality problems for most residents. Unfortunately, because residents no longer have to worry about their water supplies, they are now less concerned about groundwater protection (John Wagner, personal communication 2010). Some homeowners still have to contend with sinkholes and subsidence beneath and adjacent to their houses, although reports of this occurring are rare, probably because of the difficulty inherent in selling a house prone to land subsidence (Panno et al. 2008d).

GUIDE TO THE ROUTE

Start: Holiday Inn St. Louis-Southwest (Viking), 10709 Watson Rd., St. Louis, Missouri 63127 (877-410-6681). Set your odometer to zero.

Miles to next point	Miles from start	
0.4	0.4	Start by going west on Watson Road/Missouri 366 toward Sunset Office Drive.
6.9	7.3	MERGE onto I-270 south toward Memphis.
8.4	15.7	I-270 South becomes I-255 East crossing into Illinois.
0.3	16.0	Take Exit 9 toward Dupo.
2.4	18.4	MERGE onto Industrial Drive.
0.3	18.7	TURN SLIGHT RIGHT onto Falling Springs Drive.
0.08	18.8	TURN RIGHT onto LePere Lane.
0.01	18.8	2002 LePere Lane, Dupo, Illinois, is on the left.

Stop 1: Falling Springs, Dupo, Illinois.

0.2	19.0	Leave Stop 1. Go northeast on LePere Lane toward Falling Springs Drive.
0.1	19.1	TURN SLIGHT RIGHT to stay on LePere Lane.
1.0	20.1	LePere Lane becomes McBride Avenue.
1.8	21.9	TURN RIGHT onto Stolle Road.
4.0	25.9	TURN SLIGHT RIGHT onto Triple Lakes Road.
0.01	25.9	7508 Triple Lakes Road, East Carondelet, Illinois, is on the left.

Stop 2: Sparrow Creek Cave Spring, East Carondelet, Illinois.

0.9	26.8	Leave Stop 2. Go southeast on Triple Lakes Road/County Road P53 toward Black Oak Lane. Continue ahead.
1.6	28.4	TURN RIGHT onto Bluffside Road/County Road 0430 East. Continue to follow Bluffside Road.

0.6	29.0	TURN LEFT onto Stemler Road. CAUTION: Portions are unpaved.
0.01	29.0	2016 Stemler Road, Columbia, Illinois, is on the right.

Stop 3: Stemler Cave Woods Nature Preserve, Columbia, Illinois.

0.4	29.4	Leave Stop 3. Go east on Stemler Road toward Country Estates Drive. CAUTION: Portions are unpaved.
0.6	30.0	TURN RIGHT to stay on Stemler Road.
1.0	31.0	TURN RIGHT onto Triple Lakes Road/Country Road P53.
0.9	31.9	TURN LEFT to stay onto Triple Lakes Road/Country Road P53.
3.0	34.9	TURN RIGHT onto Illinois 158.
0.3	35.2	TURN SLIGHT RIGHT onto Illinois 3 going south.
1.3	36.5	TURN RIGHT onto Hill Castle Road, Columbia, Illinois.
0.01	36.5	Continue ahead to Columbia Saline Spring.

Stop 4: Columbia Saline Spring, Columbia, Illinois.

1.3	37.8	Leave Stop 4. Go north on Hill Castle Road toward Hill Castle Drive.
7.0	44.8	TURN RIGHT onto Illinois 3, going south.
2.3	47.1	TURN RIGHT onto Park Street/Illinois 156. Continue ahead.
0.8	47.9	TURN SLIGHT RIGHT onto Trout Camp Road, Waterloo, Illinois.
0.01	47.9	Continue 0.1 mile past Copperhead Hill Lane to Camp Vendeventer.

Stop 5: Camp Vandeventer, Waterloo, Illinois.

0.8	48.7	Leave Stop 5. Head southeast on Trout Camp Road toward Copperhead Hill Lane.
0.1	48.8	TURN SLIGHT LEFT onto Illinois 156.
0.01	48.8	3699 Woodpecker Lane, Waterloo, Illinois, is the next stop.

Stop 6: Fountain Creek Stone Bridge, Waterloo, Illinois.

4.8	53.6	Leave Stop 6. Proceed west on Illinois 156 toward Trout Camp Road.
1.8	55.4	Illinois 156 becomes East Main Street.
0.5	55.9	TURN SLIGHT RIGHT onto Quarry Road.
0.3	56.2	TURN RIGHT onto Limestone Lane.
0.03	56.2	TURN RIGHT onto Boulder Boulevard.
0.01	56.2	1423 Boulder Boulevard, Valmeyer, Illinois, is on the left.

Stop 7: Rock City, Valmeyer, Illinois.

0.03	0.03	Set odometer to zero. To return to the hotel, go west on Boulder Boulevard toward Limestone Lane.
0.4	0.4	TURN LEFT onto Limestone Lane.
12.8	13.2	TURN RIGHT onto Bluff Road.
0.8	14.0	Continue ahead to go onto Bluff Road/Country Road 6. Continue to follow County Road 6 North.
0.1	14.1	Country Road 6 North becomes Palmer Road.
0.5	14.6	MERGE onto Illinois 3 North via the ramp on the LEFT toward I-255.
6.8	21.4	MERGE onto I-255 South via the exit on the LEFT toward St. Louis County crossing into Missouri.
5.2	26.6	MERGE onto I-270 North.
1.0	27.6	EXIT on Exit 5A onto Missouri 366 East/Watson Road.
0.6	28.2	TURN SLIGHT RIGHT onto Watson Road/Missouri 366 East.
0.01	28.2	The Holiday Inn is 10709 Watson Road.

STOP DESCRIPTIONS

Stop 1: Falling Springs, Dupo, Illinois

Appendix Figures A1 and A2 show the location of Falling Springs as it appears in 2005 USGS National Aerial Photography Program (NAPP) aerial photographs and USDA 1940 Agricultural Adjustment Administration (AAA) aerial photographs. Both photographs reveal the karst terrain on the highlands above the spring and development of the area. For example, the quarry to the southwest was not in operation in 1940. Also, whereas sinkholes are prominent within the forested areas of the 2005 photograph (acquired under leaf-off conditions), the sinkholes in agricultural fields are prominent in the 1940 photograph (acquired under leaf-on conditions and during a drought).

Falling Springs is a perched cave spring that discharges from a 1- by 2-m cave along a bedding plane about midway up a steep, 50-m bluff (Figure 15). The bluff is predominantly Mississippian-age St. Louis Limestone capped by several meters of Ste. Genevieve Limestone (Zakaria Lasemi and Rodney Norby, ISGS geologists, personal communication 1998) and is located along the eastern edge of the Mississippi River Valley. The spring water cascades over a reddish black tufa deposit that has encrusted local vegetation. Tufa is a porous deposit of calcium carbonate that is associated with calcareous springs and seeps.

Historically, the spring was used as a source of fresh water. Among other uses, during the late 1800s and early 1900s, the spring supplied water to steam locomotives that served nearby limestone quarries (Figure 15). More recently, a 30-cm-wide iron trough near the base of the tufa apron was installed in about 1970 and currently supplies water to adjacent fish ponds (Figure 16a). Based on the fact that the tufa has now grown over the trough and extends beyond it by about 45 cm, the growth rate of the tufa near the base of the apron is approximately 2 cm/yr. Precipitation of minerals from the spring water is so rapid that leaves from the fall may be found totally encrusted with calcite before they get washed away by spring time flooding. Tufa on the right of the apron (Figure 16a) is continually removed with a backhoe so that water continues to fill the trough. Other small cave openings are visible in the bluff at approximately the same stratigraphic horizon as that of Falling Springs. Most of the openings have little or no flow even after a heavy rainfall (Bowman and Reed 1907). However, residents in the area report that an opening just to the north of Falling Springs discharges sediment-laden water during and immediately following large recharge events (Cliff LePere, owner, personal communications 2010).

Beneath a dry cave opening immediately to the south of Falling Springs is a tufa deposit that is far larger than that of the tufa apron of Falling Springs. In fact, subsequent to deposition of the southern tufa deposit, dissolution by dilute spring water produced a small tunnel through the tufa deposit (Figure 16b). Preliminary results of carbon-14 dating of fossil invertebrates from a similar tufa deposit at the base of Terry Spring, located about 15 km to the south along the Mississippi River bluff, yielded an age of 10,840 ± 170 years BP (Webb et al. 1998a), suggesting tufa deposition near the end of the Wisconsinan glaciation and the beginning of the Holocene (Webb et al. 1996).

The chemical composition of water from Falling Springs is controlled by the dissolution of limestone. The calcium-bicarbonate groundwater is saturated, for most of the year, with respect to calcite, aragonite, dolomite, and quartz (Panno et al. 1999). Aeration, agitation, and change in the partial pressure of carbon dioxide (CO_2) of the spring water results in the release of CO_2 from the water and causes the tufa to precipitate along the bluff face (Herman and Lorah 1987). The aeration of the spring water along the bluff causes iron oxyhydroxide to precipitate, darkening the tufa apron (Figures 15 and 16b).

Davis et al. (1989) examined the tufa deposit and its biota in detail and described the deposit, which starts out on a ledge a few meters below the mouth of the cave, as a 1-m-high cone-shaped mound that fans out like a curtain between the ledge and the bottom of the bluff, becoming more massive near the base. The tufa is about 5 m wide and 5 cm thick at the lip of the ledge and 7 m wide and up to 55 cm thick at the bottom.They reported that the most dominant organism on the apron was blue-green algae, the most abundant species being *Phormidium incrustatum.* Moss and a bacteria-laden mucilage were also observed on the tufa. The strands of algae and moss are apparently being encrusted by calcite, forming tangled clusters of parallel to subparallel, finger-like projections that make up the apron. X-ray fluorescence analysis determined that calcium, magnesium, silicon dioxide, and iron were dominant at the surface of the tufa (Davis et al. 1989).

Discharge from the spring at base flow is clear and was measured at approximately 38 L/s (Panno and Weibel

Figure 15 Falling Springs is a perched cave spring near Dupo, Illinois, that discharges from a bedding plane cave in the upper St. Louis Limestone. The perched cave spring bears witness to the rapid entrenchment of the Mississippi River valley, probably during the Pliocene to early Pleistocene Epoch. In the early 1900s, the spring was used to supply water for domestic use and for steam locomotives (inset). The railroad, steam locomotives, and water towers are gone today, but the spring now provides water for nearby fishing ponds (from Panno et al. 2009).

Figure 16 (a) The base of Falling Springs showing a 30-cm-wide trough that was installed by Cliff LePere (right) and his brother in 1970 to channel water to nearby fish ponds. The tufa has grown completely over the trough on the left, but has been trimmed back by a backhoe on the right (note teeth marks of backhoe shovel). (b) Dissolution conduit in tufa adjacent to Falling Springs formed by very rapid recharge in the upland area, possibly during a major climate change event. (Photographs by Samuel V. Panno.)

1999). During and following heavy rains, discharge typically is laden with suspended solids, and the volume of discharge appears to be one to two orders of magnitude greater than that of base flow. As with most springs in the sinkhole plain, water quality from Falling Springs is extremely poor. The water is contaminated with TC, FC, and FE derived from both natural and anthropogenic sources. Given the likely recharge area of the spring, bacteria sources probably include wastes from livestock, pets, and private septic systems as well as naturally occurring bacteria. Bacterial concentrations of water samples from the spring contained total aerobic bacteria counts of 300,000 cfu/100 mL of water, TC counts of 4,000 cfu/100 mL, and FC and FE counts of 12 and 120 cfu/100 mL, respectively (Panno et al. 2001).

Based on the chemical composition of the water issuing from Falling Springs at base flow, it is apparent that the water is a mixture of highly reduced groundwater oversaturated with respect to calcite and lesser amounts of bacteria-laden shallow groundwater. Given the abundance of suspended sediments in the spring water under high flow conditions, it would appear the dominant source of water during high flow comes via sinkholes (Figures 17 and 18). Sinkhole density in the highlands above Falling Springs is estimated to be as high as 56 sinkholes/km^2 (Panno et al. 2009b).

Figure 17 A well-manicured sinkhole pond on uplands above Falling Springs showing a nearly perfect circle. (Photograph by Samuel V. Panno.)

Figure 18 A more typical sinkhole of the sinkhole plain showing the center of the depression is a tangle of oak trees and smaller vegetation. (Photograph by Samuel V. Panno.)

Stop 2: Sparrow Creek Cave Spring, Carondelet, Illinois

Figures A3 and A4 show the location of sinkholes on the highlands that we will visit on the way to Sparrow Creek Cave Spring. These aerial photographs from 1940 and 2005 reveal the karst terrain and development of the area surrounding the spring. The sinkholes are most obvious in the 1940 photograph during drought conditions. The sinkhole shown in Figure 17 is prominent in both photographs, but the surrounding sinkholes are very clearly visible in the 1940 photograph.

Sparrow Creek Cave Spring, located near East Cardondelet, Illinois, is a partially submerged, 5-m-wide, 2-m-high opening at the base of a steep, loess-covered, blind stream valley (Figure 19). The stream issuing from the cave opening is the resurgence of the Stemler Cave groundwater basin, the headwaters of Sparrow Creek, and one of the largest springs in the state. The groundwater basin is about 7 km long and 2 km wide with an area of approximately 18 km^2 (Aley et al. 2000). Sparrow Creek Cave is hydrologically connected to Stemler Cave to the south. Sparrow Creek Cave consists of a 245-m-long, northwest-trending passage that leads to a sump and a 300-m-long side passage that becomes constricted at its distal end (Sherrill 1989). At low flow, water discharges from the cave at a rate of about 470 L/s (Panno et al. 2001). The highest discharge measured at Sparrow Creek Spring was 11,360 L/s following a heavy rainfall (Sherrill 1989).

Figure 19 Sparrow Creek Cave Spring, one of the largest springs in the sinkhole plain, is located near Carondelet just northeast of Columbia, Illinois. (Photograph by Samuel V. Panno.)

Stop 3: Stemler Cave Woods Nature Preserve, Columbia, Illinois

Figures A5 and A6 show the location of Stemler Cave Woods Nature Preserve as it appeared on aerial photographs from 1940 and 2005. Both photographs reveal the karst terrain on the highlands. The 2005 photograph shows the greater extent of the forested area and the sinkholes within. Again, the 1940 photograph is much better at showing the sinkholes within agricultural areas due to the dry conditions of the time.

Stemler Cave was named after the landowners on whose property the cave entrance was located (Figure 20). The property was initially settled by the Stemlers back in the early 1800s. Until the 1950s, the cave was used to store eggs and dairy products because of its cooler temperatures during summer. Stemler Cave and its extension, Sparrow Creek Cave, are branchwork-type caves, developed within the St. Louis Limestone, that drain the Stemler Cave groundwater basin. The crevice entrance of Stemler Cave is 15 m long and 5 m wide and is oriented in an east-west direction. The main trunk of Stemler Cave is approximately 1.8 km in length and trends northwest-southeast (Webb et al. 1998b); the cave parallels the axis of the Waterloo-Dupo Anticline. Dye tracing shows that the cave probably extends to the south, but a zone of collapsed rock prevents access to the upstream passages. During low flow, groundwater flows through Stemler Cave at a rate of 150 L/s; downstream in the groundwater basin, about three times that volume discharges from Sparrow Creek Cave (Panno et al. 2001). During periods of high flow, Stemler Cave completely floods, and the brown, sediment-laden water backs up 6 m or more in its 23-m-deep sinkhole entrance. The cross section morphology of Stemler Cave passages is predominantly elliptical, suggesting a phreatic origin for the cave. The log cabin on the property is a rare two-story cabin that was built by German immigrant Johann Georg Stemler in 1836 (Figure 21).

In 1986, the Stemler Cave Woods Nature Preserve, a 120-acre remnant of old growth, dry upland forest was dedicated and is maintained by the Illinois Department of Natural Resources. Sinkholes in the area create microclimates that result in black and white oak trees dominating the upper parts of the sinkholes and red oak trees dominating the lower parts. In 2004, thanks to extensive efforts by The Karst Conservancy of Illinois, the nature preserve (now over 4,500 acres) and the Stemler Cave groundwater basin received a Class III: Special Resource Groundwater designation from the Illinois Environmental Protection Agency in order to help protect the biodiversity of the cave and karst system (Illinois Environmental Protection Agency 2005).

Stop 4: Columbia Saline Spring, Columbia, Illinois

There are at least two saline springs in the sinkhole plain: one located near Columbia, Illinois, along the crest of the Waterloo-Dupo Anticline and the other near the Village of Valmeyer (Salt Lick Point) along the crest of the Valmeyer Anticline. Saline springs were extremely important to the survival of settlers in the area during the 1700s and early 1800s. Salt was needed to preserve meat and fish during the warmer months because of the lack of refrigeration. Because of the isolated nature of the midwestern United States during that time, settlers had to either obtain salt from local sources or buy salt from nearby salt works. At that time, the only sources of salt in the Midwest were saline springs. In about 1850, most small salt works went out of business because of the influx of cheaper salt from the Kanawha salt works in West Virginia (Kurlansky 2002). The perceived medicinal properties of the saline springs were exploited between 1850 and 1875, and mineral spas similar to those of Europe sprang up around the country at many saline springs. These were extremely popular, but only a few are still in business today (e.g., the posh West Baden Springs Hotel in southern Indiana). However, most of these spas went out of business in the early 1900s with the advent of modern medicine and financial problems related to The Great Depression (Panno et al. 2010).

There is no record of the use of Columbia Spring (Figure 22) as a source of salt during this period. However,

Figure 20 The entrance to Stemler Cave, like the entrance to Illinois Caverns, is an east-west–trending solution-enlarged crevice at the bottom of a sinkhole. Stemler Cave is located just east of Columbia, Illinois (from Panno et al. 1999).

Figure 21 This two-story log cabin was built by the Stemlers in 1836 and overlooks a large sinkhole just to the south that is the entrance to Stemler Cave. The property was chosen by the Stemlers in order to use the cave for storage of eggs and dairy products during summer months (Homer Stemler, personal communication 1995). (Photograph by Samuel V. Panno.)

Figure 22 Columbia Saline Spring is located just south of Columbia, Illinois, and discharges groundwater with a salt (NaCl) concentration of about 11,600 mg/L. Iron sulfide (FeS) precipitates on the stream gravels within and downstream of the spring, and white, filamentous, sulfur-oxidizing bacteria form mats at the mouth of and downstream of the spring (from Panno et al. 1999).

it has been reported that a salt works was developed at a saline spring along the base of the Mississippi River bluff near Valmeyer, Illinois, at a location known as Salt Lick Point. The saline springs at that location were used by Native Americans and settlers; the springs are no longer there and may have been destroyed as a result of limestone mining from the late 1800s until about 2000. The site of these springs is now part of a 240-ha Salt Lick Point Land and Water Reserve developed by the Village of Valmeyer. Another saline spring salt works near Chalfin Bridge (now Chalfin Bridge, Illinois) in Monroe County has been described in the literature (Fliege 2002). During the time that the salt works was reported to have operated, Chalfin Bridge was a small bridge crossing Maeystown Creek located 4.8 km south of Monroe (Hackworth 1883). However, a local historian expressed doubts that such a salt works ever existed at Chalfin Bridge.

The only known saline spring still flowing in the area is located just southeast of the city of Columbia, Illinois. Columbia Saline Spring is a small saline spring in a wooded area that discharges to a small stream. The spring is located along the Waterloo-Dupo Anticline in the vicinity of petroleum exploration and production. Petroleum deposits associated with traps within the Ordovician Kimmswick Formation along the anticline have been produced in this area since the 1920s (Brian Trask, ISGS, personal communications 2010). Petroleum in the area is located in traps within the Mississippian and Pennsylvanian strata along the Waterloo-Dupo Anticline. Subsequent gas storage activities known as the Waterloo Project that occurred between 1951 and 1973 (Buschbach and Bond 1973) may have initiated and/or increased flow at the spring. However, the fact that the chemical composition of the spring has remained constant over the past 15 years suggests the spring is a natural feature.

Figures A7 and A8 show the location of the Columbia Saline Spring as it appeared on aerial photographs from 1940 and 2005. No karst features are visible in the photographs because the area is underlain by Mississippian-age Warsaw Formation and Salem Limestone. The rocks (carbonate rock and shale) of the Warsaw Formation are visible in the bluffs and creek bed near the saline spring. The 2005 photograph more clearly shows the streams and spring locations. The spring is located at a tight bend in a small stream and occurs along a prominent east-west–trending lineament (Panno, unpublished data). Columbia Spring was an elliptical depression in a stream valley located along the headwaters of Carr Creek about 4 km south-southeast of Columbia, Illinois. Until about 2005, the depression was 10 m long, 5 m wide, and 1 m deep, and it was

Figure 23 White mats of sulfur-oxidizing bacteria take up white native sulfur within their filaments resulting in a striking contrast between the dark, sulfide-coated stream bed and the snowy white filamentous bacteria. (Photograph by Samuel V. Panno.)

lined with limestone cobbles coated with a black iron sulfide precipitate (Figure 22). Today, the depression has been filled with stream gravels by floodwaters, and the saline water discharges from a depression within the stream and from beneath the gravels that filled the original depression. The spring has a strong hydrogen sulfide (H_2S) odor and discharges from one of the edges of the depression where thick mats of white, filamentous, chemolithoautotrophic, sulfide-oxidizing bacteria are present (Figure 23). These bacteria are common at saline springs throughout the Illinois Basin (Panno et al. 2010) and typically consist of filamentous Epsilonproteobacteria and Gammaproteobacteria (Engel et al. 2004). Members of this group of sulfur-oxidizing bacteria consume H_2S and, during metabolism, generate sulfuric acid; these bacteria have been implicated in sulfuric acid speleogenesis (Engel et al. 2004). The H_2S concentration discharging from the sediment immediately adjacent to the spring was measured by the

authors at 3 ppm. The threshold for detecting H_2S in air is 0.00047 ppm (Powers 2004). Concentrations of 10 to 20 ppm can lead to eye irritation; 100 to150 ppm can deaden the sense of smell, cause eye damage, and cause coughing; 250 to 500 ppm causes nausea, disorientation, and pulmonary problems; and concentrations from 500 to 1,000 ppm can cause rapid loss of consciousness and death (U.S. Environmental Protection Agency 1980).

Immediately downstream of the spring, there are thick bacterial mats that appear white because the some of the filamentous bacteria contain native sulfur (orthorhombic) (Figure 23). During dry summer months, particles of native sulfur can be seen in such abundance that the stream takes on a milk color (Figure 24). The white filamentous bacteria extend for about 0.2 km downstream where their white strands are in stark contrast to the sulfide-blackened bedrock and gravels. The pronounced depression and shape of the original spring location indicated that it was probably a dissolution feature. That is, saline groundwater coming up from depth mixed with shallow calcium-bicarbonate-type groundwater and formed a more aggressive water capable of dissolving limestone due to mixing corrosion (e.g., Back et al. 1986) and/or by bacterially mediated sulfuric acid formation that dissolved the underlying the carbonate rock. The chemical composition of the spring is NaCl-type water with Na and Cl concentrations of 3,510 and 8,080 mg/L, respectively. The spring water is slightly acidic (pH 6.7) and is discharging from Mississippian-age limestone along the axis of the Waterloo-Dupo Anticline. The Cl/Br ratio of the spring water suggests a relatively deep origin, perhaps a mixture of saline groundwater from Ordovician and Cambrian strata.

Figure 24 During summer months and at low flow, the stream becomes filled with particulates of native sulfur and becomes milk colored. (Photograph by Samuel V. Panno.)

Saline springs are indicators of preexisting pathways from deep within the basin to the surface, which is an important consideration when sites are being selected for facilities for geologic sequestration of CO_2. Panno et al. (2010) determined that saline springs found throughout the Illinois Basin were located along geologic structures within and at the margins of the Basin. Approximately 40 saline spring locations have been identified, and we are currently sampling them and using their halide ratios and stable isotope and chemical compositions to determine their source formations. Many saline springs are now located in state parks because of the unusual nature of the geology and hydrogeology of these sites. A few are located at remaining mineral spas, and the others are only locally known and are located on private lands.

Stop 5: Camp Vandeventer, Waterloo, Illinois

Camp Vandeventer is located 6 km west of Waterloo, Illinois, and is owned by the Boy Scouts of America (BSA). The camp provides outdoor activities for the scouts amid an intensely karstified landscape. Figures A9 and A10 show the location of the Camp Vandeventer as it appeared on aerial photographs from 1940 and 2005. The 2005 photograph most clearly shows the karst features within the forested areas and the highly angular nature of Fountain Creek. The camp straddles Fountain Creek, a relatively large stream that dissects part of the sinkhole plain (Figure 25). The BSA rented this site until 1928; at that time, Judge Wilton M. Vandeventer of East St. Louis purchased 27.5 ha and established a permanent camp for the scouts (Voris 1998).

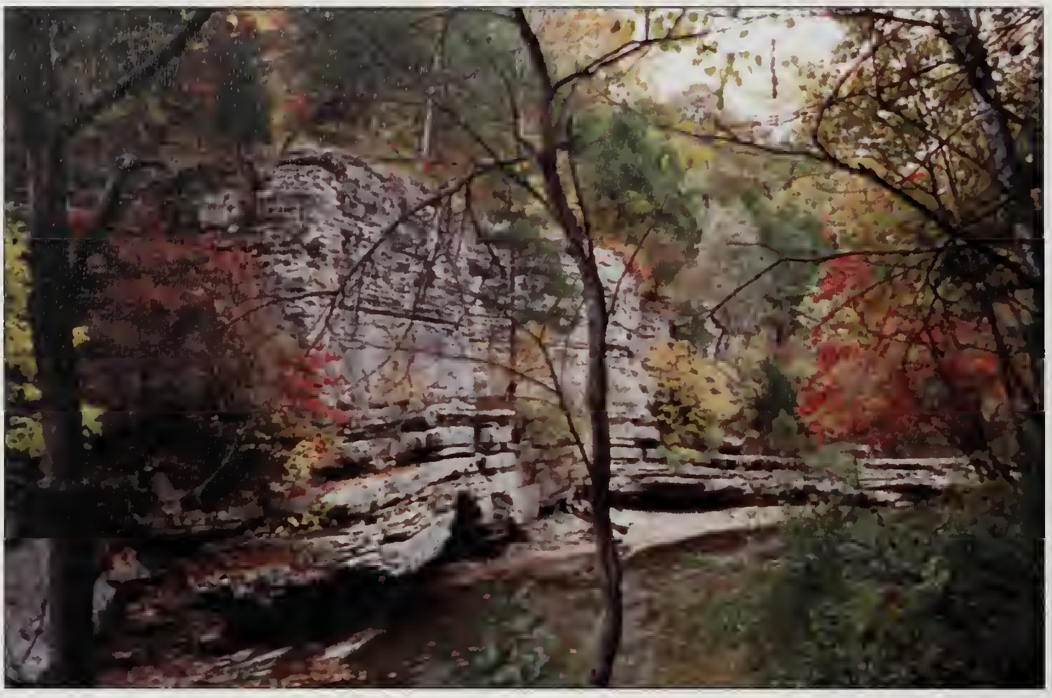

Figure 25 Limestone bluffs of the well-bedded St. Louis Formation bound Fountain Creek and show numerous dissolution features. (Photograph by Samuel V. Panno.)

The camp is a picturesque geological setting containing limestone canyons and bluffs, numerous sinkholes and sinkhole ponds, a karst window, caves, springs, and a seasonally sinking and resurgent stream. The beds of limestone exposed throughout Camp Vandeventer belong to the Mississippian-age St. Louis Formation.

The winding entrance road passes by numerous sinkholes that display a wide range of sizes, depths, and types. Across from the Apache Camp site (on the road) is a 14-m-deep karst window (Figures 26 and 27). A karst window is a sinkhole that forms as a result of the collapse of a cave roof to land surface. The water flowing through this karst window continues to the west as a cave stream and discharges at a spring at the base of a 12- to 14- m bluff just below the camp's old mess hall to Fountain Creek (Figure 28) (Aley and Aley 1998). Following a particularly heavy rainfall event (e.g., 5 cm in 8 hours or less), the karst window fills with runoff, overflows, and spills into a ravine leading to Fountain Creek.

Fountain Creek is the largest stream in Monroe County and can be quickly transformed into a raging torrent by runoff from heavy rainfall. During times of low flow, Fountain Creek is a sinking or losing stream. Voris (1998) reported that, during particularly dry periods, the stream may flow completely underground for a few hundred meters downstream of the mess hall. The creek water returns to the surface channel about 0.4 km downstream and eventually flows into the Mississippi River about 16 km west of Camp Vendeventer. Rainfall and snowmelt on the plateau drains, for the most part, into nearby sinkholes and discharges into Fountain Creek via numerous springs along the base of the bluffs along the creek including those of Camp Vandeventer.

The spring at the base of the 12- to 14–m-high bluff located just below the camp's mess hall discharges from a small cave in the St. Louis Limestone (Figure 28). Discharge from the spring was measured at 35 L/s at low flow (Aley and Aley 1998). The spring flows directly into Fountain Creek through an entrenched channel that at one time was the water source for the camp. As with most springs in the sinkhole plain, water samples from this spring are always contaminated with fecal coliform bacteria; the spring is among the most severely contaminated in the sinkhole plain. The dominance of *Escherichia coli* and the presence of optical brighteners in the spring water suggest that private septic systems are a primary source of contamination (Panno et al. 2001; Joan Bade, sanitarian, Monroe and Randolph County Health Departments, personal communications 1997). The rRNA source tracking suggested both human and pig sources (W.R. Kelly, Illinois State Water Survey, unpublished data).

Another cave is located just to the west of the spring along the same bluff (Figure 29). Usually, discharge from this cave is almost negligible. However, the spring

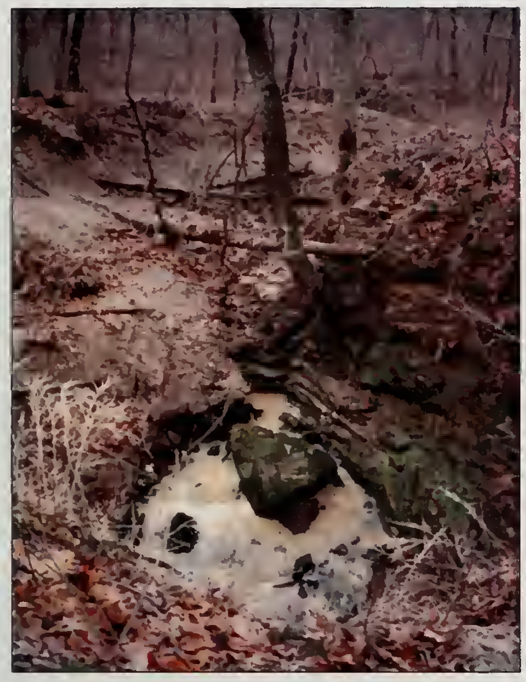

Figure 26 The karst window at Camp Vandeventer formed when the roof of a cave collapsed and formed this 11-m-deep cavity. Groundwater flows from the far side of the window, disappears into the near side, and flows to Camp Vandeventer Spring. (Photograph by Samuel V. Panno.)

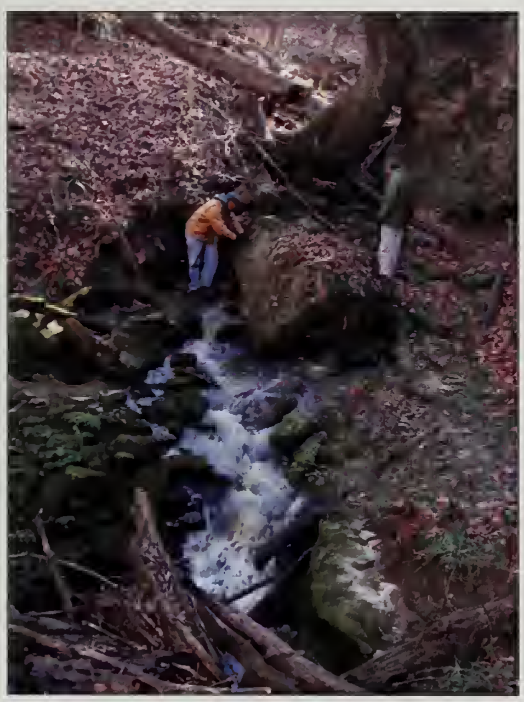

Figure 27 View of the karst window from the bottom. Moss on the rocks and lower parts of the walls suggest the presence of a microclimate in this area. (Photograph by Samuel V. Panno.)

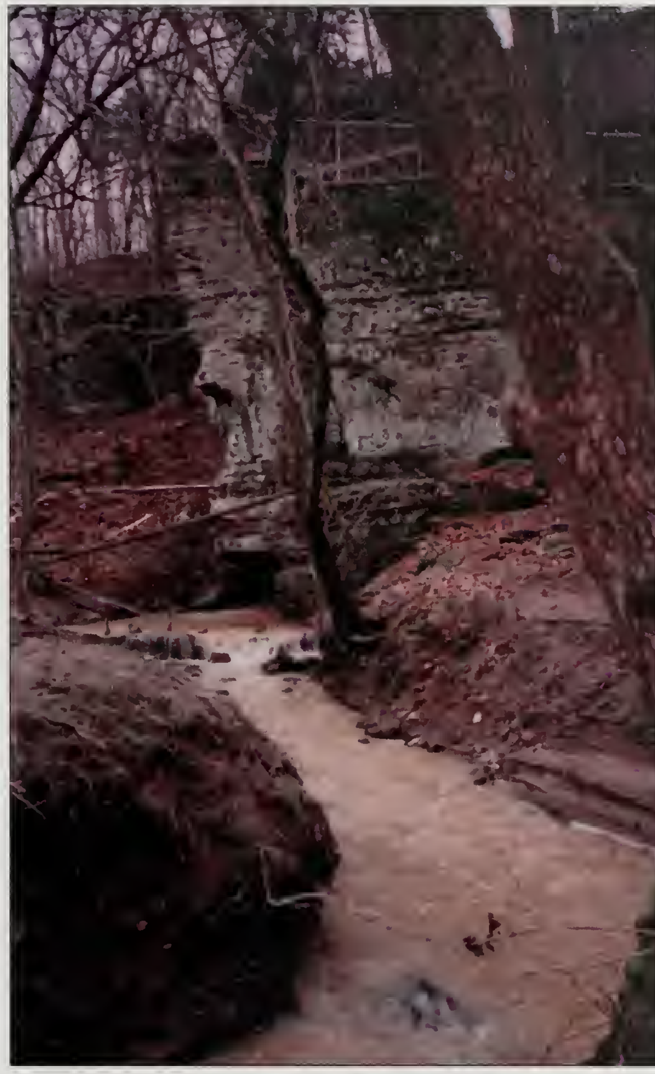

Figure 28 Camp Vandeventer Spring, located at the base of the limestone bluff just below the camp's mess hall, is a typical large cave spring in Illinois' sinkhole plain. (Photograph by Samuel V. Panno.)

Figure 29 Geochemist Keith Hackley examines collapsed slabs of limestone just outside of a small cave spring adjacent to the Camp Vandeventer Spring. (Photograph by Samuel V. Panno.)

is an overflow for the Camp Vandeventer Spring during flooding (Panno et al. 1996), when discharge is characteristically high-energy, turbulent flow, and both springs discharge many hundreds to >1,000 L/s.

The bluff on the opposite side of Fountain Creek is a classic exposure of St. Louis Limestone that displays numerous dissolution features (Figure 25). The upper portion of the bluff contains vertical joints that allow surface water to move downward into bedrock. Small amounts of water move laterally along bedding planes and can be seen discharging from the bluff wall and flowing down the bluff face. A small, sediment-filled cave passage is visible at the base of the bluff.

STOP 6: Fountain Creek Stone Bridge, Waterloo, Illinois

Figures A11 and A12 show the location of the Fountain Creek Stone Bridge just to the south of Camp Vendeventer as it appeared on aerial photographs from 1940 and 2005. Although this bridge is no longer in use, it has been preserved and is located just south of Route 156 about 3 km west of Waterloo and can be seen just south of the roadway. A trace of the old road that crossed the stone bridge is still visible on the 1940 photograph. Karst features surround the bridge, and the angular nature of Fountain Creek is most apparent in the 2005 photograph where the stream orientation corresponds to lineaments and solution-enlarged crevice orientations. The stone bridge was one of the first built in Monroe County (1849) from limestone quarried from the area and is one of the largest in the area (Figure 30). The bridge was used to cross Fountain Creek until 1927. Similar arched stone bridges are common in the sinkhole plain. Early settlers to southwestern Illinois took advantage of the abundance of limestone in the area for construction of houses, buildings, and bridges and as lining for hand-dug wells (Figure 31). A few houses and numerous arched stone bridges can still be seen in southwestern Illinois. Today, limestone quarries are common features in the sinkhole plain, and the limestone is used for aggregate and building materials.

Figure 30 Fountain Creek Stone Bridge, located just west of Waterloo, Illinois, on Route 156, was built from locally quarried limestone in 1849. (Photograph by Samuel V. Panno.)

Figure 31 This now abandoned building at Valmeyer Quarry is another example of the use of natural materials for construction in southwestern Illinois (Panno et al. 1999).

Figure 32 Chert is commonly found as masses and in tabular form along beds of the Upper St. Louis Limestone (here along the bluffs of Fountain Creek) and was used by Native Americans in the area. (Photograph by Samuel V. Panno.)

Upstream of the bridge is an excellent exposure of the upper St. Louis Limestone showing prominent, thin bedding planes and abundant chert weathering out of the rock (Figure 32). Chert was used by Native Americans in the area for tools and other implements. Along several of these bedding planes, there is evidence of dissolution and groundwater discharge to the stream. Numerous anastamoses, small springs, and small caves can be seen. During low flow, a prominent limestone bed provides a pavement that makes for easy walking upstream. Within this pavement, a small spring discharging from the base of the bluff has created an incised channel about 10 cm wide and 10 cm deep that meanders like a stream channel (Figures 33 and 34). We suggest that the channel initially formed along a bedding plane where its pathway was affected by the irregular surface of the limestone bed. The channel is actively being downcut by aggressive shallow groundwater from locally recharging rainfall and snowmelt and abrasion by sediments. Just upstream, Fountain Creek makes a sharp 90 degree turn to the east (Figures A11 and A12); because this is one of several angular

Figure 33 The bluffs of Fountain Creek reveal many karst features, including caves and springs. The Fountain Creek stream bed, seen here just south of the stone bridge, is a bedding plane surface on which dissolution features may be seen. To the left of the photograph is a small spring that discharges from the base of the bluff and created a sinuous incised channel to the stream. (Photograph by Samuel V. Panno.)

Figure 34 (a) The incised channel (from Figure 33) showing the relationship between the sinuosity and the texture of the surface of the bedding plane. The inset of this channel reveals the stream-like details of the channel. (b) Detail of the incised channel showing organic debris within the channel and preferential dissolution and abrasion along the leeward sides of the meanders (Photograph by Samuel V. Panno.)

Figure 35 Nick point just after a 90 degree turn in Fountain Creek just upstream from the incised channel showing the tabular bedding of the St. Louis Limestone. (Photograph by Samuel V. Panno.)

turns for this creek, and because one of the dominant joint directions in the sinkhole plain is east-west, it is likely that the trace of Fountain Creek is joint controlled. Just beyond that point, a nick point in the limestone has created a small steplike waterfall that reveals bedding of the St. Louis Limestone (Figure 35).

Stop 7: Rock City, Valmeyer, Illinois

Rock City is a joint venture of the Village of Valmeyer and Admiral Parkway Inc. that rents the now closed Valmeyer Quarry as storage space. The Village of Valmeyer was originally located on the floodplain of the Mississippi River but was destroyed by a 1.5-m wall of water and associated flooding that resulted from a breached levy during the Great Flood of 1993. With the help of federal grants, the village relocated in a karst area on top of the bluff overlooking the Mississippi River and created infrastructure for the new Village of Valmeyer and for Rock City.

Quarrying operations of the former Columbia Stone Company ceased in 1992 after operating for more than 120 years (Figure 36). The quarrying operations were conducted along the Mississippi River bluffs in the late 1800s and early 1900s, and the rock was used for agriculture soil amendments and roadbed ballast for the Missouri-Pacific Railroad. Mining later went underground extracting the Ordovician-age Dunleith Forma-

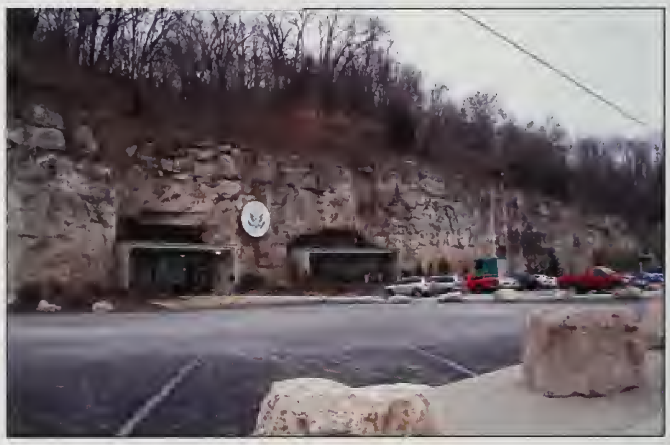

Figure 36 Mine openings in massive Ordovician-age limestone are commonly seen along the bluffs of the Mississippi River near the Village of Valmeyer. These mines are currently being used for storage and refrigeration at Rock City. (Photograph by Samuel V. Panno.)

tion of the Kimmswick Subgroup (Figure 37). The rock is a coarse-grained, light gray to white limestone that is about 30 m thick in this area and is exposed along the crest of the Valmeyer Anticline. Mississippian-age rocks are exposed along both flanks (Frankie et al. 1997). The limestone that was mined is massive in character with no apparent karst features. Figures A13 and A14 show the location of Rock City as it appeared in USGS NAPP aerial photographs from 1940 and 2005. The 1940 photograph shows the quarrying operations as white patches, and the 2005 photograph shows the Rock City operations as they appear today.

Figure 37 The limestone along the Mississippi River bluffs were mined using room and pillar methods with ceiling heights of 10 m. Mining from the early 1870s to 1992 resulted in over 500,000 m^2 of mined out area (Photograph by Samuel V. Panno).

Currently, the Rock City operation has 557,400 m^2 of area within the old mine workings. As much as 465,000 m^2 of this area has been taken up by the National Archives and Records Administration for storage of retired military personnel records and other materials. Another 18,600 m^2 has been converted to a cold (frozen) storage space. Here, foods such as Girl Scout cookies, pizza, and ice cream products are stored until they are ready for distribution (Lori Magg, manager of Rock City, personal communications, 2010).

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Appendix: Aerial Photographs

Figure A1 USGS National Aerial Photography Program (NAPP) aerial photograph of the Falling Springs and upland karst area acquired on March 3, 2005.

Figure A2 USDA Agricultural Adjustment Administration (AAA) aerial photograph of the Falling Springs and upland karst area acquired on June 25, 1940.

Figure A3 USGS NAPP aerial photograph of the Sparrow Creek Cave Spring and upland karst terrain acquired on March 3, 2005.

Figure A4 USDA-AAA aerial photograph of the Sparrow Creek Cave Spring and upland karst terrain acquired on June 25, 1940.

Figure A5 USGS NAPP aerial photograph of the Stemler Cave Woods Nature Preserve area and associated karst terrain acquired on March 3, 2005.

Figure A6 USDA-AAA aerial photograph of the Stemler Cave Woods Nature Preserve area and associated karst terrain acquired on June 30, 1940.

Figure A7 USGS NAPP aerial photograph of the Columbia Saline Spring area acquired on March 3, 2005.

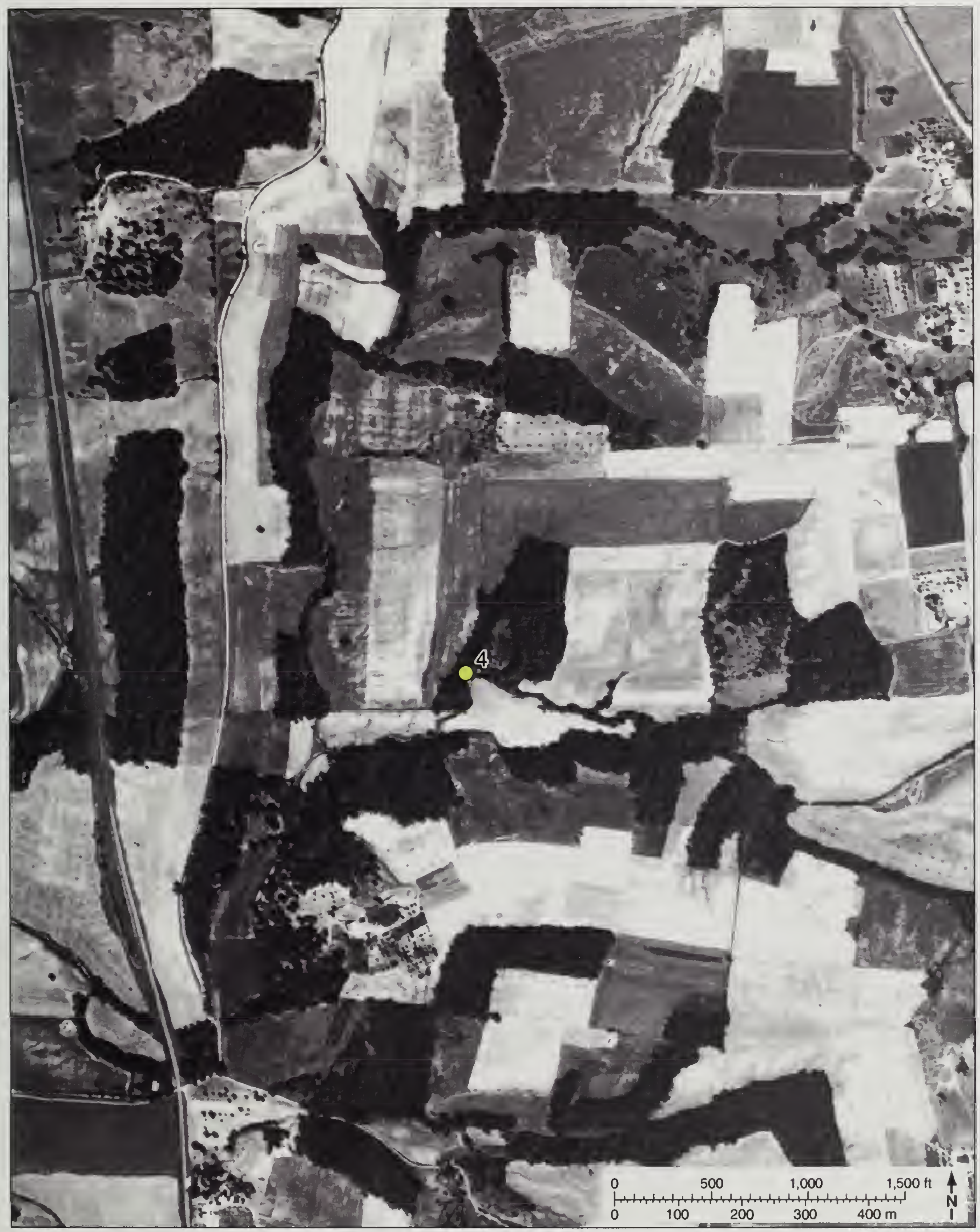


Figure A8 USDA-AAA aerial photograph of the Columbia Saline Spring area acquired on June 25, 1940.

Figure A9 USGS NAPP aerial photograph of the Camp Vandeventer area and associated karst terrain acquired on March 3, 2005.

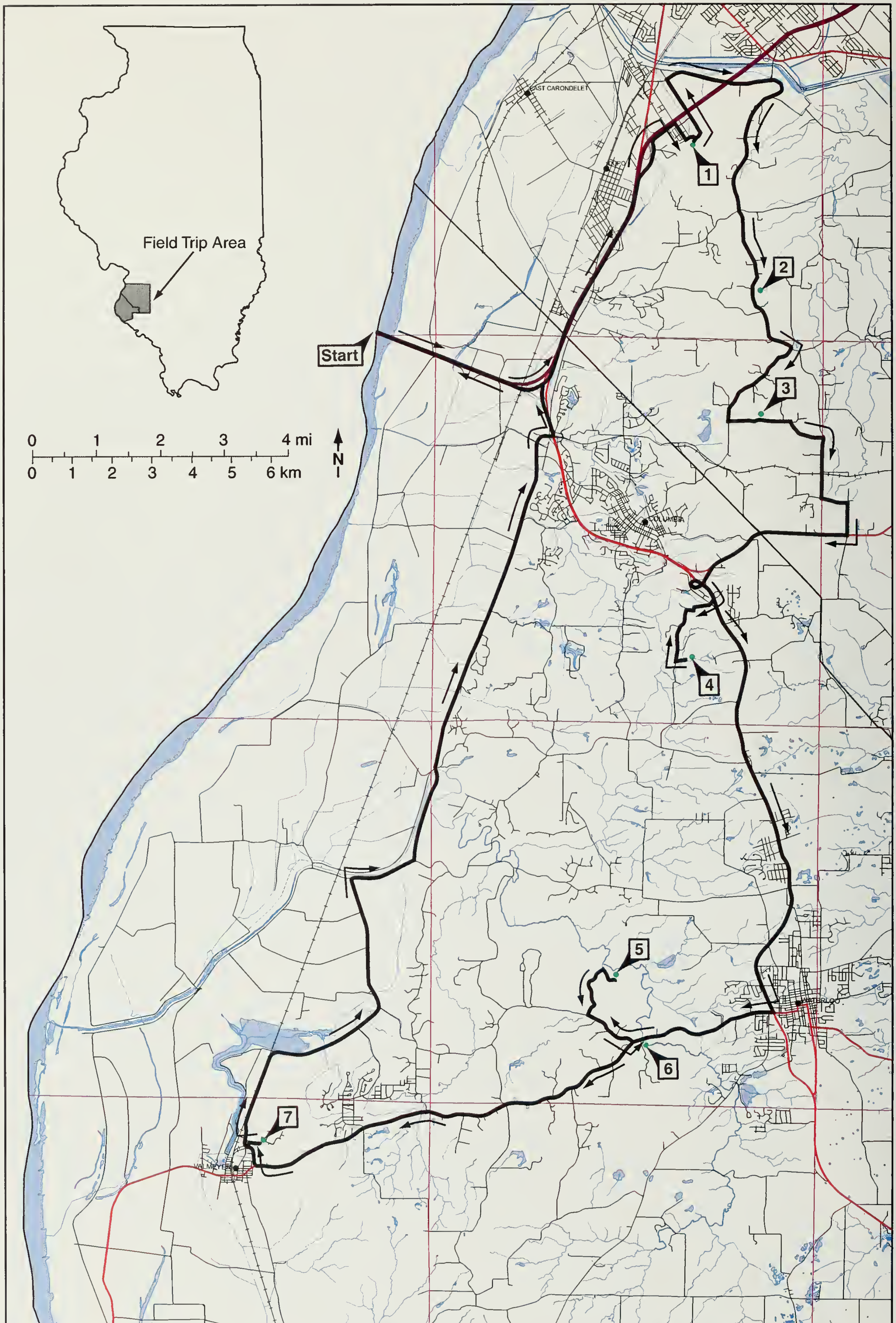
Figure A10 USDA-AAA aerial photograph of the Camp Vandeventer area and associated karst terrain acquired on September 5, 1940.

Figure A11 USGS NAPP aerial photograph of the Fountain Creek Stone Bridge area and associated karst terrain acquired on March 6, 2005.

Figure A12 USDA-AAA aerial photograph of the Fountain Creek Stone Bridge area and associated karst terrain acquired on September 5, 1940.

Figure A13 USGS NAPP aerial photograph of the Rock City area acquired on February 25, 2005, showing the roadways and parking area of the new storage facilities.

Figure A14 USDA-AAA aerial photograph of the Rock City area acquired on July 17, 1940, showing the areas where mining operations were taking place (white patches).



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